CLINICAL EXPERIENCE WITH THE BABB-GRIMSRUD HIGH EFFICIENCY DIALYSER

ALBERT L. BABB, LARS GRIMSRUD and BELDING H. SCRIBNER
Departments of Nuclear Engineering and Medicine, University of Washington, Seattle, Wash., U.S.A.

INTRODUCTION

Before presenting the clinical results obtained with the Babb-Grimsrud dialyser a brief summary will be given of the considerations on which the present design was based.

Grimsrud and Babb (1966) developed a mathematical model for predicting the performance capability of a dialyser in terms of the resistance encountered by a solute in passing from the blood through a membrane and into the dialysate. This overall mass transfer resistance, $R_o$, may be calculated from

$$R_o = 3a/(2D\lambda_i^2)$$  \hspace{1cm} (1)

where $a$ is the blood channel half-height, $D$ is the diffusivity of the solute species, and $\lambda_i^2$ is a parameter that depends only on the membrane permeability $P$ in terms of the dimensionless group Pa/D. Tabulated values of $\lambda_i$ as a function of Pa/D are given elsewhere in these transactions (Grimsrud and Babb, 1967). This mass transfer resistance is the only valid index for comparison of one dialyser with another because it establishes the mass transfer rate for one square centimetre of dialyser membrane and for a unit blood-to-dialysate concentration difference.

It is important to note that from a clinician’s point of view the performance of a given dialyser assembly in relation to its effectiveness in removing toxic substances from blood is adequately measured by determination of the clearance. However, the clearance is influenced by such factors as membrane area and blood-to-dialysate concentration differences, whereas the mass transfer resistance is not and is a constant for a given dialyser. Thus, the mass transfer resistance describes the efficiency with which the membrane available is being utilized and is therefore the best basis for comparison of one dialyser with another.

The optimum blood film half-thickness, $a$, to be used for the calculation of $R_o$ from equation 1 is obtained from the results of an earlier analysis by Grimsrud and Babb (1964). This analysis showed that for a dialyser of given length for which a maximum arterial-venous pressure drop is specified the mass transfer rate of a particular solute exhibits a sharp maximum when plotted against the blood film thickness. In fact, the unique blood film half-thickness, $a$, at the maximum value can be calculated from

$$a = (4/\mu/\Delta PR_o)^{1/3}$$  \hspace{1cm} (2)

where $l$ is the length of the dialyser (excluding connecting lines), $\mu$ is the blood viscosity, $\Delta P$ the pressure drop across the dialyser, and $R_o$ the mass transfer resistance. It was also found that the shorter the dialyser the higher the mass transfer rate will be at its maximum value.

* This work was supported by the John A. Hartford Foundation and by Contract No. PH 43-66-932 from the National Institute of Arthritis and Metabolic Diseases, National Institutes of Health, USPHS, HEW.
To calculate \( a \) from equation 2, the membrane permeability \( P \) can be used in place of \( 1/R_a \) to give a first approximation to \( a \). Once \( a \) is estimated, \( R_a \) can be calculated from equation 1 and used in equation 2 for the calculation of a new \( a \) and so on. One iteration is usually sufficient. For our first attempt at constructing an optimized dialyser we picked \( l = 20 \) cm from practical considerations. The other system constants employed have the following approximate values:

Maximum pressure drop across dialyser: Given by the conditions of the heart, veins and arteries, \( 50,000 \) dynes/cm\(^2\) \((37.5 \) mm Hg\)

Blood viscosity: \( 3 \times 10^{-2} \) dyne sec. / cm\(^2\)

Membrane permeability, urea, cuprophan: \( 37^\circ \)C.: \( 1/18 \) cm/min.

With the use of these values in equations 1 and 2 the optimum blood channel height for the reference dialyser is \( 0.02 \) cm and the theoretical overall mass transfer resistance for urea is \( R_a = 21 \) min./cm.

To calculate the actual mass transfer resistance, \( R_a \) of an operating dialyser for comparison with theoretical values the following relationships are useful:

Counter-current blood and dialysate flow

\[
R_a = A \frac{(Q_B - Q_B)}{(Q_BQ_B)} \log_e \left[ \frac{(Q_B - K)/Q_B}{(Q_B - K)/Q_B} \right] \quad (3)
\]

and

Parallel flow

\[
R_a = -A \frac{(Q_B + Q_B)}{Q_BQ_B} \log_e \left[ 1 - K \frac{(Q_B + Q_B)}{Q_BQ_B} \right] \quad (4)
\]

where \( A \) is the membrane area, \( K \) is the solute clearance, \( Q_B \) and \( Q_D \) are the blood and dialysate flow rates, respectively. The solute concentration in the entering dialysate is assumed to be zero.

It is of interest to compare the actual mass transfer resistance of a Kiil dialyser with the theoretically attainable value of \( 21 \) min./cm for the reference dialyser \( 20 \) cm long having a blood channel half-height of \( 0.02 \) cm. From Figure 1 it is seen that at a blood flow rate of \( 200 \) ml/min the average in vivo urea resistance is \( 90 \) min./cm compared to \( 21 \) min./cm for the reference dialyser. Because cuprophan PI 150 (1 ml, wet thickness) has a urea mass transfer resistance of only \( 18 \) min./cm at \( 37^\circ \)C., it is evident that \( 80\% \) of the mass transfer resistance (of \( 72 \) min./cm) in the Kiil dialyser is in the fluid films. Part of this resistance is caused by channeling in both the blood and dialysate compartments. The clinical significance of this can be seen from Figure 2. The Kiil dialyser with a membrane area of \( 1 \) m\(^2\) and a mass transfer resistance of \( 90 \) min./cm has an expected urea clearance of \( 80 \) ml/min at a blood flow rate of \( 200 \) ml/min. To give the same urea clearance the reference dialyser with a resistance of \( 21 \) min./cm theoretically requires a membrane area of only \( 0.24 \) m\(^2\). On the other hand, the reference dialyser with \( 1 \) m\(^2\) of membrane area would have a theoretical urea clearance of \( 164 \) ml/min.

The high fluid film resistance of the Kiil dialyser is caused largely by the V-groove membrane support shown on the left side of Figure 3. The tendency of the membrane to sag between the supports creates a blood channel whose thickness is both large and variable which results in an uneven blood distribution in the dialyser. The blood film thickness also
Fig. 1. A comparison of in vivo urea mass transfer resistances for the Kiil and Babb-Grimsrud dialysers with the theoretical value for a dialyser with a length of 20 cm and a blood channel height of 0.02 cm.

Fig. 2. The effect of membrane area on the urea clearance calculated for the Kiil dialyser (R = 90 min./cm) and a dialyser with a theoretically attainable mass transfer resistance of 21 min./cm.

Fig. 3. A comparison between the Kiil membrane support and a foam metal support.
is influenced greatly by the pressure in the dialysate compartment, i.e., it depends on the ultrafiltration requirements. Similar variations in blood film thickness are characteristics common to all haemodialysers presently in use.

Since, as discussed above, dialyser performance can be maximized only if the blood film thickness is fixed within a very narrow range, it becomes necessary to discard all former approaches to membrane support such as the Kiil grooves and to try to develop a dialyser based on a flat fully supported membrane that would give a blood channel height within a few percent of the theoretical optimum under all operating conditions. Several types of supports were tested by us and other investigators, but the improvements were rather marginal until we tried a foam nickel support (Babb and Grimsrud, 1964). This is a nickel foam with interconnected pores and a nominal density of 3% of the solid nickel. The pore diameter ranges from 0.02 cm to 0.13 cm and the web thickness from 0.1 to 0.05 cm. This support, which could also be made from glass or plastic, is illustrated on the right hand side of Figure 3. The membrane sag has been practically eliminated so that the optimum blood

![Fig. 4. Assembly diagram of the two-layer Babb-Grimsrud dialyser.](image)

channel height can be maintained, the blood volume changes very little with dialysate pressure, and the reduction in membrane surface area due to contact with the foam is less than 5%. Another important beneficial effect, however, is on the dialysate side where local eddies are created such that the dialysate side mass transfer characteristics are also the same as if the flow were turbulent. This turbulent effect also reduces the dialysate resistance.

An assembly diagram of the most recent foam nickel dialyser is shown in Figure 4. The overall length is 30 cm and the width 45 cm. The two-layer unit has a membrane area of 0.38 m² and a blood volume of 76 ml whereas the three-layer unit has a membrane area of 0.5 m² and a blood volume of 90 ml. The dialysers are operated in a vertical position with the blood flowing upwards. The dialysate also enters at the bottom and flows essentially parallel to the blood flow.

**RESULTS OF CLINICAL STUDIES**

Mass transfer resistances calculated from 15 in vivo dialyses are compared with similar data
for the two-layer Kiil dialyser under the same conditions and with the same membrane (cuprophane) in Figure 1. It will be noticed that the Babb-Grimsrud (B-G) dialyser has a mass transfer resistance that is on the average about three times lower than the Kiil dialyser. The spread in the experimental mass transfer resistances is very small compared to that of the Kiil. The B-G data are essentially independent of blood flow rate in contrast to the Kiil, where the mass transfer resistance increases sharply at low blood flow rates because of excessive channeling due to the large and variable blood film thickness. The effectiveness of the support material in the B-G dialyser is also indicated by the small increase in blood volume which is less than 10% when the pressure difference across the membrane is increased from 0 to 400 mm Hg.

Since the mass transfer resistance for urea in the B-G dialyser is about three times lower than the Kiil, the two-layer B-G unit with about 1/3 the surface area should have about the same urea clearances as the two-layer Kiil according to equations 3 and 4. This has been confirmed by the clearance data shown in Table I in which in vivo results are given for the Kiil, modified chronic coil, and B-G dialysers. It is also of interest to note the comparison between the three dialysers in terms of the urea clearance per unit of blood volume and per unit of membrane surface area. The decrease in clearance per unit area for the B-G dialysers as the total area is increased can be predicted from Figure 2.

Finally, typical BUN-time curves for the Kiil and two- and three-layer B-G dialysers are given in Figure 5. It is seen that the urea level in the blood reached by the three-layer B-G dialyser in 11 hours required about 15 hours for the Kiil and two-layer B-G dialysers. Thus, the three-layer B-G dialyser offers the possibility of twice daily use in dialysis centres. In Table II, urea and creatinine data are presented for a recent dialysis with a three-layer B-G dialyser.

Summary

It has been shown that it is theoretically possible to decrease the mass transfer resistance by a factor of 3 to 4 as compared to present day haemodialysers by closely controlling the blood film thickness and by inducing mixing on the dialysate side. This has been accomplished by using a foam nickel membrane support. Other foam materials such as glass and ceramic are being investigated. At present, a series of both two- and three-layer dialysers are being constructed for testing under routine operating conditions at the University of Washington Hospital.
### TABLE I

Comparison between typical in vivo urea clearances for Kiil, chronic coil and Babb-Grimrud dialysers

<table>
<thead>
<tr>
<th>Dialyser</th>
<th>Membrane area, m²</th>
<th>Blood vol., ml</th>
<th>Flow rates, ml/min</th>
<th>Urea clearance ml/min</th>
<th>Urea clearance/ml min⁻¹</th>
<th>Urea clearance/cm² min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiil (2-layer)</td>
<td>1.0</td>
<td>350</td>
<td>200</td>
<td>500</td>
<td>85</td>
<td>0.24</td>
</tr>
<tr>
<td>Chronic coil*</td>
<td>0.9</td>
<td>450</td>
<td>200</td>
<td>500</td>
<td>90</td>
<td>0.20</td>
</tr>
<tr>
<td>B-G (2-layer)**</td>
<td>0.38</td>
<td>76</td>
<td>200</td>
<td>600</td>
<td>91</td>
<td>1.2</td>
</tr>
<tr>
<td>B-G (3-layer)**</td>
<td>0.50</td>
<td>90</td>
<td>200</td>
<td>1600***</td>
<td>102</td>
<td>1.1</td>
</tr>
</tbody>
</table>

* Freeman, Maher, and Shreiner (1965).
** Data for patient R. B., 5/1/67. The initial serum phosphate level was 10 mg%, and at the end of the dialysis it was 3.9 mg%.
*** This includes 500 ml/min of fresh dialysate and 1100 ml/min of recirculated dialysate.

### TABLE II

In vivo results with three-layer (5000 cm²) Babb-Grimrud dialyser (blood volume 90 ml)

<table>
<thead>
<tr>
<th>Hrs</th>
<th>Min</th>
<th>Flow rates-ml/min*</th>
<th>BUN mg%</th>
<th>Urea resistance (Rₒ), min/cm</th>
<th>Urea clearance ml/min</th>
<th>Creatinine clearance ml/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dialysate** blood</td>
<td>A</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On</td>
<td>0</td>
<td>15</td>
<td>1600</td>
<td>208</td>
<td>30</td>
<td>38.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>50</td>
<td>1600</td>
<td>200</td>
<td>61</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>46</td>
<td>1600</td>
<td>217</td>
<td>49.5</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>50</td>
<td>1600</td>
<td>172</td>
<td>38</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>52</td>
<td>1600</td>
<td>238</td>
<td>29</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>55</td>
<td>1600</td>
<td>238</td>
<td>25</td>
<td>12</td>
</tr>
</tbody>
</table>

* Data for patient R.B., 5/1/67. The initial serum phosphate level was 10 mg%, and at the end of the dialysis it was 3.9 mg%.
** This includes 500 ml/min of fresh dialysate and 1100 ml/min of recirculated dialysate.
REFERENCES


